HYBRID ELECTRIC VEHICLES

UNIT-3

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1.Characteristics of traction drive - requirement of electric motors for EV/HEV's:

EV AND HEV MOTOR REQUIREMENTS

The important characteristics of a motor for an EV or HEV include flexible drive control, fault tolerance, high efficiency, and low acoustic noise. The motor drive must be capable of handling voltage fluctuations from the source. Another important requirement of the electric motor is acceptable mass production costs, which is to be achieved through technological advancement. The requirements of an EV or HEV motor, not necessarily in order of importance, are itemized in the following:

- Ruggedness
- High torque-to-inertia ratio (T_e/J); large Te/J results in "good" acceleration capabilities
- Peak torque capability of about 200 to 300% of continuous torque rating
- High power-to-weight ratio (P_e/w)
- High-speed operation, ease of control
- Low acoustic noise, low electromagnetic interference (EMI), low maintenance, and low cost
- Extended constant power region of operation

2.Induction Motor drives - their control and applications in EV/HEVs:

INDUCTION MACHINES:

Squirrel cage induction motors are of greater interest for EV and HEV and most other general-purpose applications.

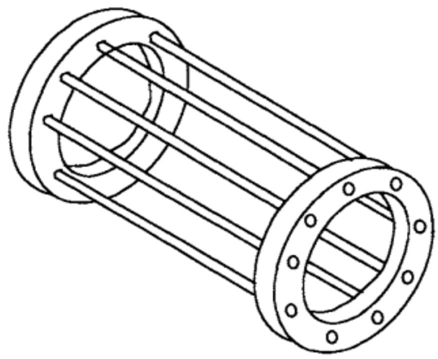


FIGURE 5.16 The squirrel cage of an induction motor.

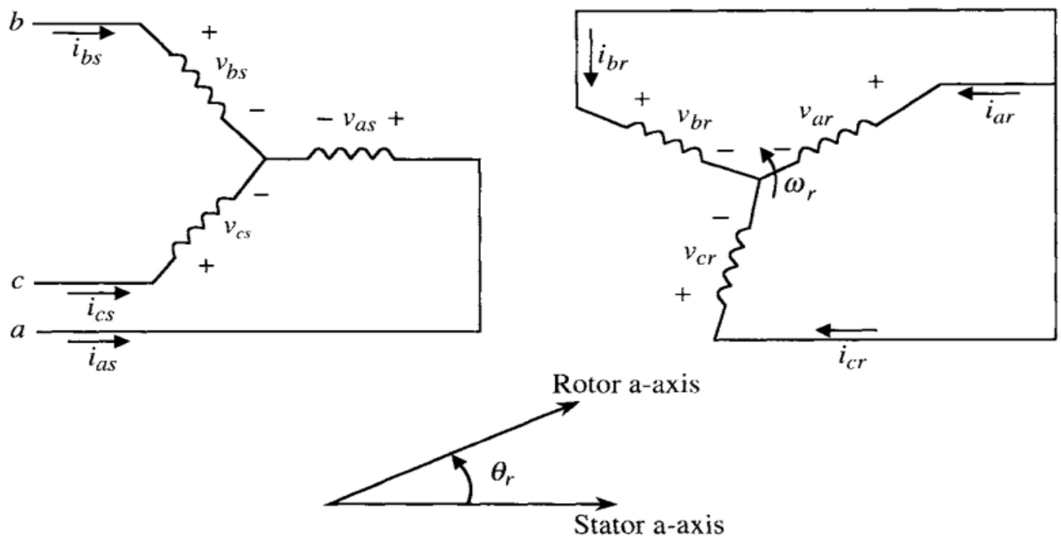


FIGURE 5.17 Stator and rotor electric circuit and magnetic axes of a three-phase induction machine.

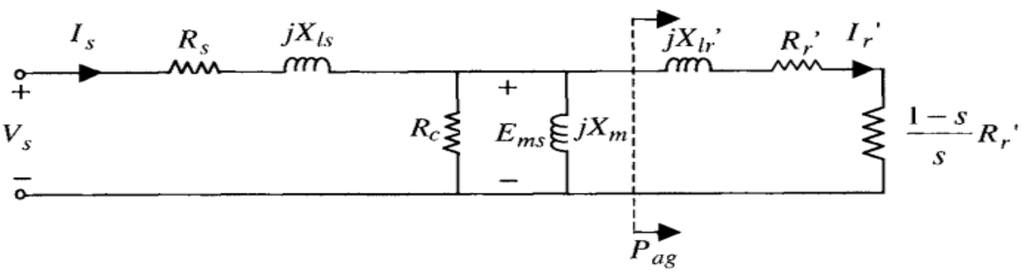


FIGURE 5.18 Steady state per-phase equivalent circuit of an induction motor.

Although the per-phase equivalent circuit is not enough to develop controllers that demand good dynamic performance like in an EV or HEV, the circuit provides a basic understanding of induction machines. The vast majority of applications of induction motors are for adjustable speed drives, where controllers designed for good steady state performance are adequate. The circuit allows the analysis of a number of steady state performance features. The parameters of the circuit model are as follows:

E_{ms}=Stator-induced emf per phase
V_s=Stator terminal voltage per phase
I_s=Stator terminal current
R_s=Stator resistance per phase
X_{ls}=Stator leakage reactance
X_m=Magnetizing reactance
X_{lr}' =Rotor leakage reactance referred to stator
R_r'=Rotor resistance referred to stator

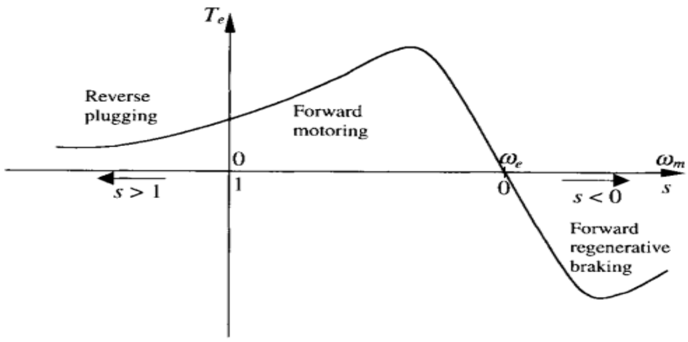


FIGURE 5.19 Steady-state torque-speed characteristics of an induction motor.

I_r'=Rotor current per phase referred to stator

Note that the voltages and currents described here in relation to the per-phase equivalent circuit are phasors and not space vectors. The power and torque relations are

$$P_{ag} = \text{Air gap power} = 3\left|I_r'\right|^2 \frac{R_r'}{s}$$

$$P_{dev} = \text{Developed mechanical power} = 3\left|I_r'\right|^2 \frac{(1-s)R_r'}{s}$$

$$= (1-s)P_{ag}$$

$$= T_e\omega_m$$

$$P_R = \text{Rotor copper loss} = 3\left|I_r'\right|^2 R_r'$$

The electromagnetic torque is given by

$$T_e = 3\left|I_r'\right|^2 \frac{(1-s)R_r'}{s\omega_m}$$

$$= \frac{3R_r'}{s\omega_s} \frac{V_s^2}{\left(R_s + R_r'/s\right)^2 + \left(X_s + X_r'\right)^2} \tag{5.30}$$

The steady-state torque-speed characteristics of the machine are as shown in Figure 5.19. The torque produced by the motor depends on the slip and the stator currents, among other variables. The induction motor starting torque, while depending on the design, is lower than the peak torque achievable from the

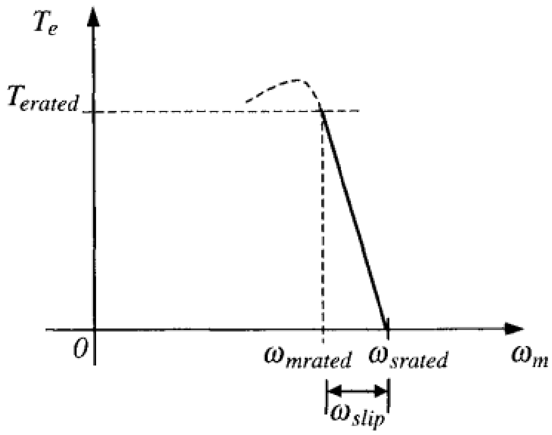


FIGURE 5.20 Torque-speed characteristics of an induction motor for rated flux condition.

motor. The motor is always operated in the linear region of the torque-speed curve to avoid the higher losses associated with high slip operation. In other words, operating the machine at small slip values maximizes the efficiency.

5.5.3 SPEED CONTROL METHODS

The speed of an induction motor can be controlled in two ways, by varying stator terminal voltage and stator frequency.

Changing the terminal voltage changes the torque output of the machine, as is evident from Equation 5.30. Note that changing the applied voltage does not change the slip for maximum torque. The speed control through changing the applied frequency is based on the frequency and synchronous speed relation $\omega_e=4\pi f/P$; changing f changes ω_e. Figures 5.22 and 5.23 show variations in torque-speed characteristics with changes in voltage and frequency, respectively. What is needed to drive the induction motor is a power electronics converter that will convert the available constant voltage into a variable voltage, variable frequency output, according to the command torque and speed. The top-level block diagram of such a drive system is shown in Figure 5.24. First-generation controllers of induction motor drives used in EVs employed slip control (constant *V/Hz* control) using a table of slip vs. torque. The performance of such a drive for vehicle applications is poor, because the concept of *V/Hz* control is based on a steady state equivalent circuit of the machine. The dynamic performance of the machine improves significantly using vector control. The *dq*-axes transformation theory for induction motors will be presented as an introduction to vector control theory in the next section, after the discussion on regenerative braking. Induction motor drives will be discussed in Chapter 8.

Figure 5.25 shows the envelope of the torque speed characteristics of an induction motor. Using a power electronics controlled drive, it is possible to achieve constant power characteristics from an induction motor at higher speeds, a feature that is so important for EV and hybrid vehicle motor drives.

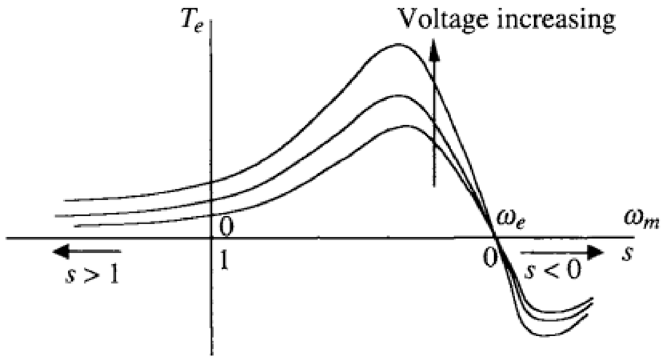


FIGURE 5.22 Torque-speed profile at different voltages with fixed supply frequency.

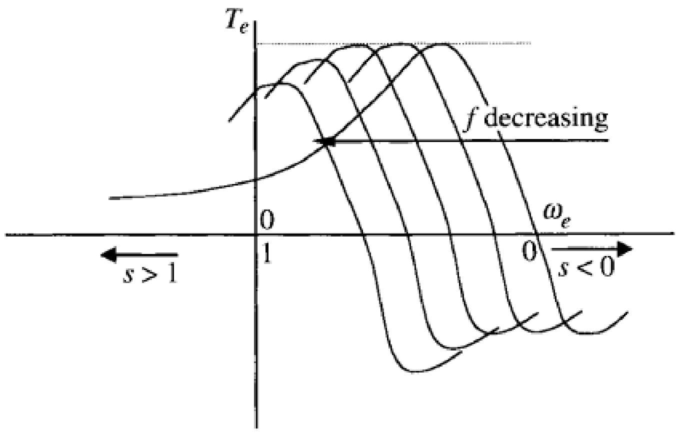


FIGURE 5.23 Torque-speed profile with variable frequency but constant V/f ratio.

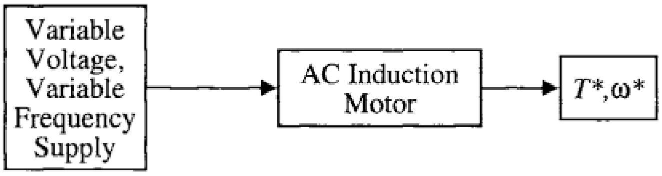


FIGURE 5.24 Induction motor drive.

5.6 REGENERATIVE BRAKING

One of the advantages of using electric motors for vehicle propulsion is saving energy during vehicle braking through regeneration. The regenerated energy can be used to recharge the batteries of an EV or HEV. It is important to note that it will not be possible to capture all of the energy available during vehicle braking, especially when sudden stops are commanded. The energy available during braking is the kinetic energy that was acquired by the vehicle during acceleration. The energy is typically too high to be processed by the electric motor used for propulsion. Processing high energy in a relatively short time would require a huge motor or, in other words, a motor with high power ratings, which is impractical. Hence, EVs and HEVs must be equipped with the

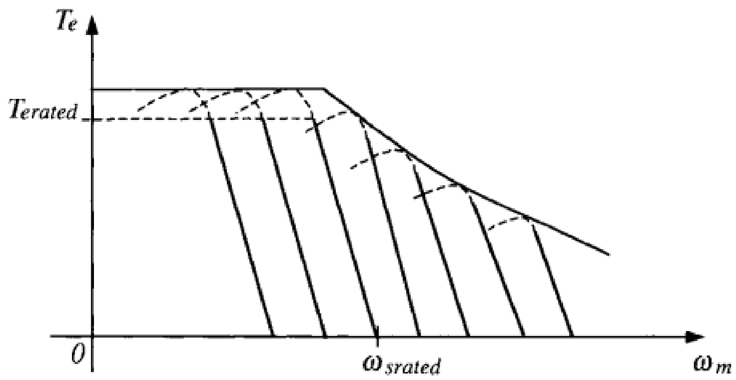


FIGURE 5.25 Torque-speed operating envelope for the induction motor.

mechanical brake system, even though the electric motor drive is designed with regeneration capability. However, regeneration can save a significant portion of energy, extending the range of a vehicle. The vehicle supervisory controller decides the amount of braking needed from the mechanical system based on the braking command of the driver, the amount of regeneration possible, and vehicle velocity.

In the regenerative braking mode, the kinetic energy of the vehicle is processed by the electric machine and returned to the energy source. From the machine perspective, this is no different than operating the machine in the generator mode. The electric machine converts the mechanical power available from vehicle kinetic energy and converts it to electrical energy—the flow of energy is from the wheels to the source. Regenerative braking can increase the range of EVs by about 10 to 15%.

The induction machine works as a generator when it is operated with a negative slip, i.e., the synchronous speed is less than the motor speed $\omega_m > \omega_e$. Negative slip makes the electromagnetic torque negative during regeneration or the generating mode. In the negative slip mode of operation, voltages and currents induced in the rotor bars are of opposite polarity compared to those in the positive slip mode. Electromagnetic torque acts on the rotor to oppose the rotor rotation, thereby decelerating the vehicle.

The motor drives for EVs are always four-quadrant drives, meaning that the electric motor is controlled by the drive to deliver positive or negative torque at positive or negative speed. The transition from forward motoring to regeneration can be explained with the help of Figure 5.26 for four-quadrant induction motor drives. The linear segments of the induction motor torque-speed curves for several operating frequencies are shown in the figure. Consider the frequencies f_1 and f_2.

The curves are extended in the negative torque region to show the characteristics during regeneration. Suppose initially, the electric vehicle is moving forward, being driven by the positive torque delivered by the induction motor, and the steady state operating point in this condition is at Point 1. Now, the vehicle driver presses the brake to slow the vehicle. The vehicle system

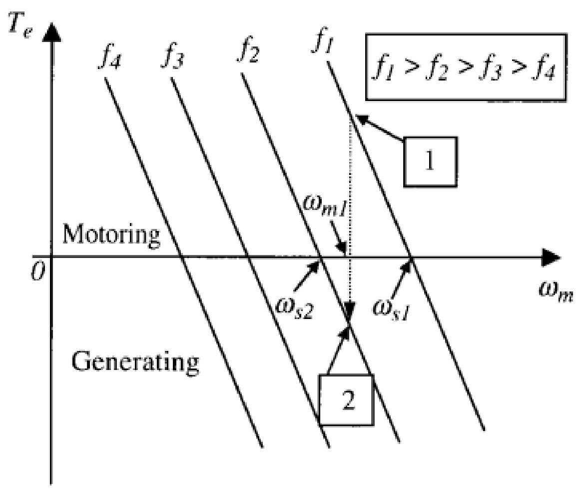


FIGURE 5.26 Transition from motoring to generating using a four-quadrant drive.

controller immediately changes the motor drive frequency to f_2 such that $\omega_{s2}>\omega_{m1}$. The operating point shifts to Point 2 immediately, because the motor speed cannot change instantaneously due to inertia of the system. At Point 2, the slip and the electromagnetic torque are negative, and the motor is regenerating. The vehicle will slow from this condition onward. As the motor speed decreases and falls below the synchronous speed, the operating frequency needs to be changed to a lower value so that generating mode operation can be maintained. The power electronics drive is responsible for establishing the shifted linear torque-speed curves with different synchronous speeds for the induction machine at different frequencies, as shown. The drive circuit does so by changing the frequency of the supply voltage. The regenerative braking mode continues as long as there is kinetic energy available and the driver wishes to slow the vehicle. Similar to starting, regeneration has to be achieved in a controlled way, so that the power rating of the machine is not exceeded. The amount of kinetic energy to be converted within the desired stopping time determines the power that is to be handled by the machine.

Vector Control Implementation

The vector-controlled drive has three major components like any other motor drive system: electric machine, power converter, and controller. An implementation block diagram of a speed-regulated vector-controlled drive is shown in Figure 8.18. The controller processes the input command signals and the feedback signals from the converter and the motor and generates the gating signals for the PWM inverter or converter.

In the closed-loop speed-controlled system, the input is a speed reference, which is compared with the measured speed feedback signal to generate the control signals for maintaining the desired speed. The vector controller requires

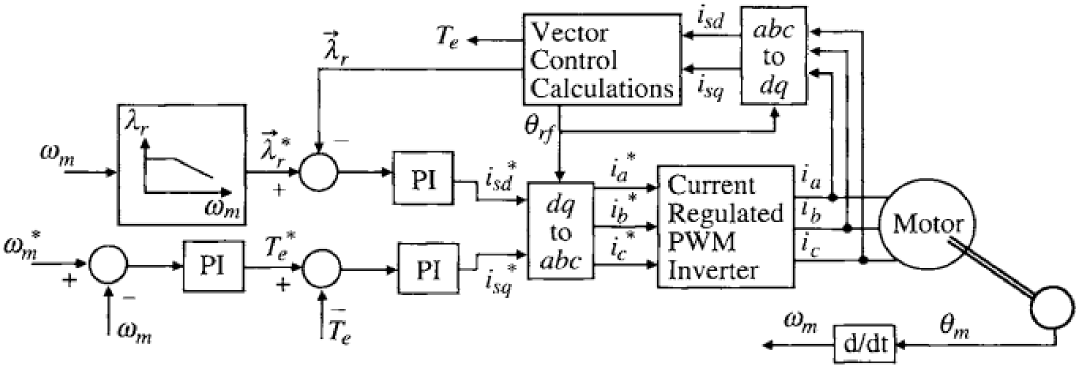


FIGURE 8.18 Implementation of vector control.

reference frame transformations and several computations that are typically implemented in a digital signal processor. The controller outputs in the first stage are the three-phase reference currents $i_a^*(t)$, $i_b^*(t)$, and $i_c^*(t)$ for the current regulated PWM inverter. The current controller in the second stage generates the PWM gating signals for the power electronics converter switches to establish the desired currents in the electric motor. Sensors provide current feedback information to the controller for vector calculations. Vector calculations involve transformation to a suitable reference and then torque and reference frame angle calculation. The torque and angle calculation can be in the rotor flux reference frame, where torque Equation 8.21 and the block diagram of Figure 8.17 are used. For speeds up to the rated speed of the machine, rated rotor flux λ_r is used. For higher speeds, the flux command is reduced to operate the machine in the constant power mode. This mode of operation is known as the flux weakening mode. In the indirect control method, position and speed sensors are used that provide rotor position and motor speed feedback information (the implementation shown in Figure 8.17).

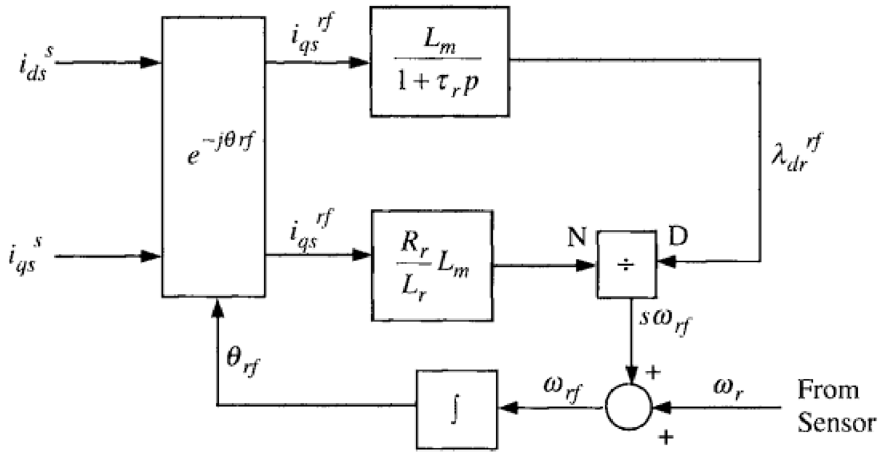


FIGURE 8.17 Rotor flux angle calculation in indirect vector control method.

3.Permanent magnet Synchronous motor: configuration - control and applications in EV/HEVs:

PM SYNCHRONOUS MOTORS

The permanent magnet synchronous motor (PMSM), also known as the sinusoidal brushless DC motor or PM DC motor is a synchronous motor, where the field mmf is provided with permanent magnets. The PMSM has high efficiency and a cooling system that is easier to design. The use of rare earth magnet materials increases the flux density in the air gap and, accordingly, increases the motor power density and torque-to-inertia ratio. In high-performance motion control systems that require servo-type operation, the PMSM can provide fast response, high power density, and high efficiency. In certain applications like robotics and aerospace actuators, it is preferable to have the weight as low as possible for a given output power. The PMSM, similar to induction and DC machines, is fed from a power electronic inverter for efficient operation of the system. Smooth torque output is maintained in these machines by shaping the motor currents, which necessitates a high-resolution position sensor and current sensors. The control algorithm is implemented in a digital processor using feedback from the sensors. A flux weakening operation that enables a constant power mode of operation is possible in PMSM by applying a stator flux in opposition to the rotor magnet flux. The motor high speed limit depends on the motor parameters, its current rating, the back-emf waveform, and the maximum output voltage of the inverter.

The permanent magnets in PMSM machines are not only expensive, but they are also sensitive to temperature and load conditions, which constitute the major drawbacks of PM machines. Most of the PMSMs are found in small to medium power applications, although there are some high-power applications for which PMSMs are used.

PMSM and induction motors have good performance in terms of torque response and have rugged motor structures, although broken magnet chips in PM machines is a concern. The slip speed calculation makes the induction motor control more complicated than that of the PMSM, as the latter has only stationary and synchronous reference frames. Without a rotor cage, PMSM has a lower inertia that helps the electrical response time, although the induction motor electrical response characteristics will be the fastest because of the smaller time constant. The electrical time constant of magnetic circuits is determined by the L/R ratio. The load current transient in induction machines is limited only by small leakage inductance, where the time constant inductance in PM machines is the much higher self-inductance. With a higher power density, the PMSM is smaller in size compared to an induction motor with the same power rating. PMSM is more efficient and easier to cool, compared to the induction machines, due to the absence of rotor copper loss. The induction motor has lower cost and cogging torque because of the absence of permanent magnets.

Rotor temperature variation is a big problem for the induction motor because it causes detuning of the field-oriented controller. The induction motor can

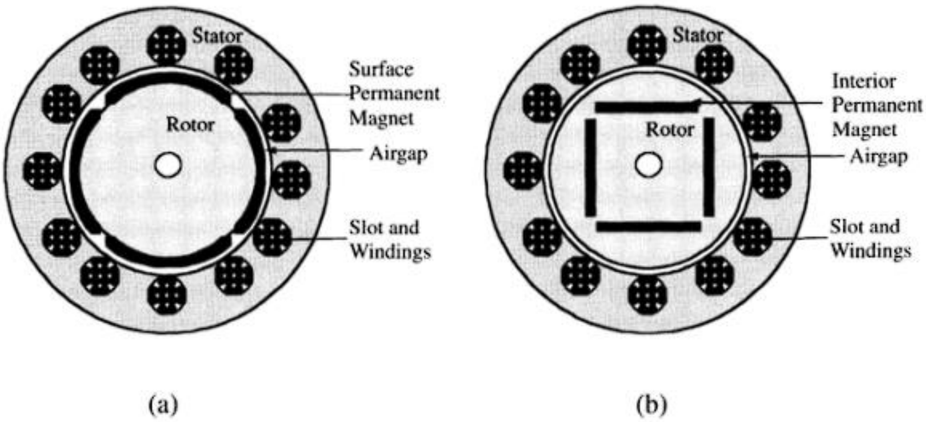


FIGURE 6.2 Permanent magnet machines: (a) surface-mounted; (b) interior.

sustain high peak current at several times the rated current without the danger of demagnetizing the magnets. However, the PMSM can also safely sustain two to three times the rated current. The major difficulty with the PMSM occurs at high speed when the eddy current in the magnet (a sintered magnet has good conductivity) causes magnet heating and may cause demagnetization. To prevent such occurrences, the magnets are sometimes split into several pieces along the axial length, which increases resistance to eddy current.

The surface-mount PM machine suffers from poor field weakening capability. The efficiency of the machine is also low at high speed due to higher core and copper losses. However, the interior PM machine has excellent field weakening characteristics. The field weakening performance of the induction machine is also satisfactory, the range being two to three times the base speed.

In the inset PMSM, magnets are put into the rotor surface slots, which makes them more secured. The direct and quadrature axes reluctances are unequal in inset PMSMs, because space is occupied by a magnet in the direct axis and by iron in the quadrature axis. The quadrature axis inductance Lq is larger than the direct axis inductance Ld, because the direct axis flux path has a larger effective air gap and, hence, higher reluctance, although the length of the air gap between the stator and the rotor is the same. The interior PMSM has its magnets buried inside the rotor. The manufacturing process is complicated and expensive for the interior PMSM. The quadrature axis inductance Lq in interior PMSMs can be much larger than the direct axis inductance Ld. The larger difference in the d- and q-axes inductances make the interior PM more suitable for flux weakening operation, delivering a wider constant power region compared to the other types of PMSMs. The extended constant power range capability is extremely important for EV and HEV applications to eliminate the use of multiple gear ratios and to reduce the power inverter volt-ampere rating. Because of the unequal reluctance paths in the direct and quadrature axes, a reluctance torque exists in buried and inset PMSMs.

Voltage and Torque in Reference Frames

The *abc* variables can be transformed into the rotor reference frame, which is also the synchronous reference frame, for synchronous machines in steady state. The stator *dq* equations of the PMSM in the *dq* or rotor reference frame are as follows:

$$
\begin{aligned}
v_q &= R_s i_q + \frac{d}{dt}\lambda_q + \omega_r \lambda_d \\
v_d &= R_s i_d + \frac{d}{dt}\lambda_d - \omega_r \lambda_q
\end{aligned}
\tag{6.1}
$$

where

$$
\begin{aligned}
\lambda_q &= L_q i_q \\
\lambda_d &= L_d i_d + \lambda_f
\end{aligned}
$$

Here, i_d and i_q are the *dq* axis stator currents, v_d and v_q are the *dq* axis stator voltages, R_s is the stator phase resistance, L_d and L_q are the *dq* axis phase inductances, λ_d and λ_q are *dq* axis flux linkages, and ω_r is the rotor speed in electrical rad/s. The subscript *s* used in Chapter 5 to refer to stator quantities for induction machines has been dropped here for simplicity. The *d* and *q* axis inductances are $L_d = L_{ls} + L_{md}$ and $L_q = L_{ls} + L_{mq}$. (L_{ls} is the leakage inductance.) Note that the *d*- and *q*-axes mutual inductances can be different in the case of PM machines. The electromagnetic torque is

$$
T_e = \frac{3}{2}\frac{P}{2}\left[\lambda_f i_q + \left(L_d - L_q\right) i_d i_q\right]
\tag{6.2}
$$

where *P* is the number of poles.

Rotor position information gives the position of *d*- and *q*-axes. The control objective is to regulate the voltages v_d and v_q or the currents i_d and i_q by controlling the firing angles of the inverter switches. The rotor position is given by

$$
\theta_r = \int_0^t \omega_r(\xi)\, d\xi + \theta_r(0)
$$

PM SYNCHRONOUS MOTOR DRIVES

The advantage of a PM synchronous machine is that it can be driven in the vector-controlled mode, delivering high performance, unlike the PM trapezoidal machine, which has to be driven more in the six-step mode. Of course, high-precision position information is needed to implement vector control in PM synchronous machines. A typical PM synchronous motor drive consists of a PM synchronous motor, a three-phase bridge inverter, gate drivers, position sensor, current or voltage sensors, a microprocessor, and its interfacing circuits, as shown in Figure 8.19.

Vector control of a PM synchronous motor is simpler than that of an induction motor, because the motor always rotates at synchronous speed. In vector calculations, only the synchronously rotating reference frame is necessary. The

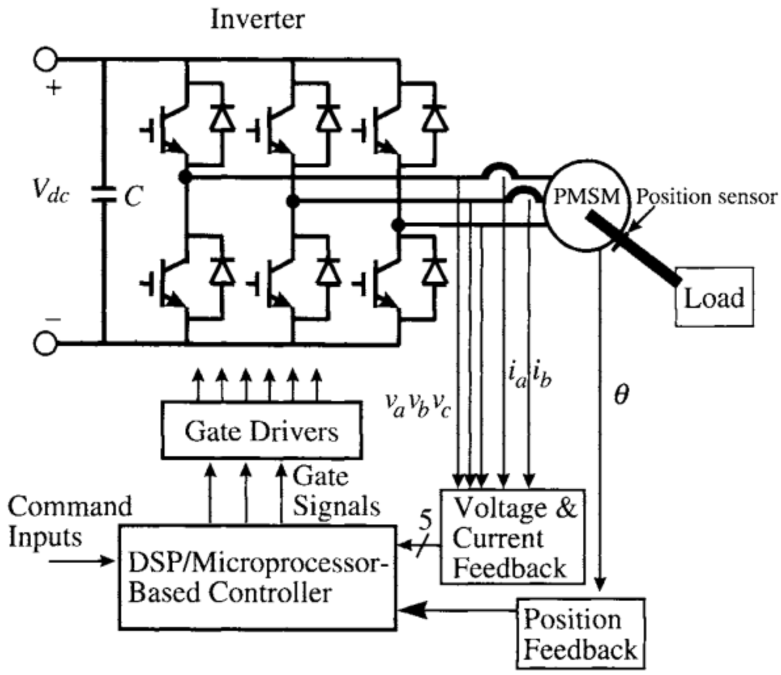


FIGURE 8.19 A typical PM synchronous motor drive structure.

system controller sets the reference or command signal, which can be position, speed, current, or torque. The variables needed for the controller are the feedback signals from the sensing circuits (position, speed, current, or voltage) or estimated values in the signal processor. The error signals between the reference and actual variable signals are transformed to gate control signals for the inverter switches. The switches follow the gate commands to decrease the error signals by injecting desired stator currents into the three-phase stator windings.

8.3.1
VECTOR CONTROL

Vector control is used for the PM synchronous motor drive in EV and HEV applications to deliver required performance. Torque Equation 6.2 for the PM synchronous motor shows that if the *d*-axis current is maintained constant, the generated torque is proportional to the *q*-axis current. For the special case when i_d is forced to be zero, $\lambda_d = \lambda_{af}$ and

$$\begin{aligned} T_e &= \frac{3}{2}\cdot\frac{P}{2}\cdot\lambda_{af}\cdot i_q \\ &= k_e i_q \end{aligned} \tag{8.28}$$

where

$$k_e = \frac{3}{2}\cdot\frac{P}{2}\cdot\lambda_{af}$$

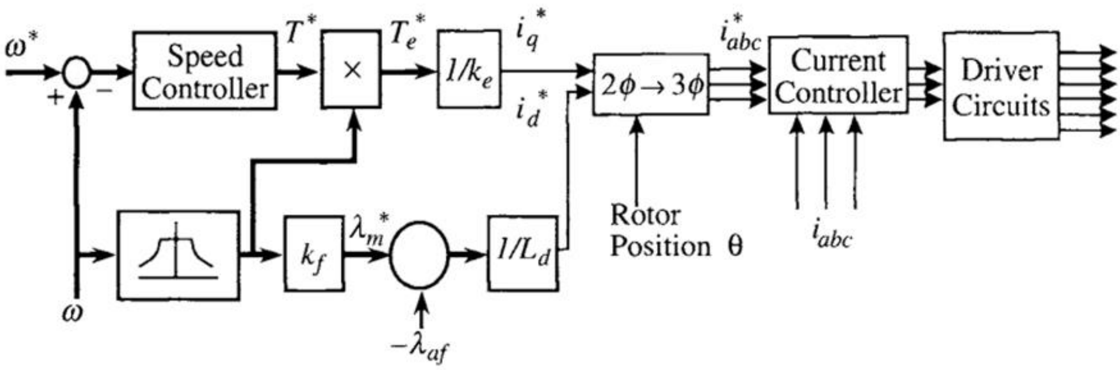


FIGURE 8.20 Vector controller structure for PMSM with field weakening.

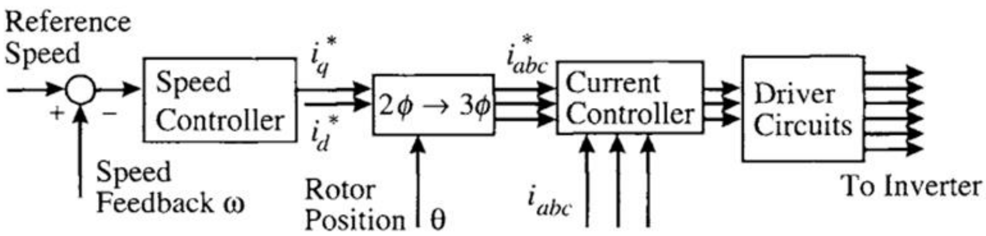


FIGURE 8.21 Current controller block diagram.

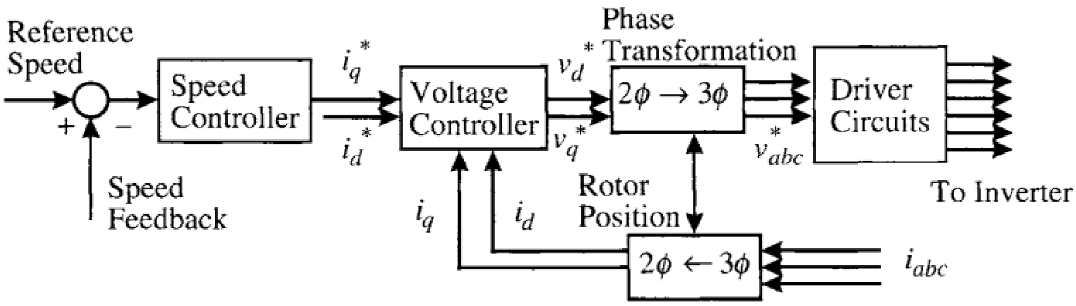


FIGURE 8.22 Voltage controller block diagram.

=motor constant. Because the magnetic flux linkage is a constant, torque is directly proportional to q-axis current. The torque equation is similar to that of a separately excited DC machine. Therefore, using reference frame transformations, the PM synchronous motor can be controlled like a DC machine.

8.3.2 FLUX WEAKENING

The PM synchronous motor can be operated in the field-weakening mode, similar to the DC motor, to extend the constant power range and achieve higher speeds. An injection of negative i_d will weaken the air gap flux as seen from Equation 6.2. The implementation technique for the field-weakening mode is shown in Figure 8.20.

CURRENT AND VOLTAGE CONTROLLERS

Current and voltage control techniques, as described in Section 8.1, are applicable to the PM synchronous motor drive. PM synchronous motor drives can be designed using a current controller with a dual-phase mode. The simplified block diagram of a current controller is shown in Figure 8.21. The drawback of the current controller can be avoided if the current error signals drive a linear controller to convert the current commands into voltage commands. The voltage command signals can then be used for a voltage PWM scheme, such as the sinusoidal PWM or the space vector PWM. The block diagram of such a method is shown in Figure 8.22.

4.Brushless DC Motors: Advantages - control of application in EV/HEVs:

PM BRUSHLESS DC MOTORS

Permanent magnet AC machines with trapezoidal back-emf waveforms are known as the PM brushless DC machines. The concentrated windings of the machine instead of the sinusoidally distributed windings on the stator are the reason for the trapezoidal-shaped back-emf waveforms. PM brushless DC motors are widely used in a range of applications, from computer drives to sophisticated medical equipment. The reason behind the popularity of these machines is the simplicity of control. Only six discrete rotor positions per electrical revolution are needed in a three-phase machine to synchronize the phase currents with the phase back-emfs for effective torque production. A set of three Hall sensors mounted on the stator facing a magnet wheel fixed to the rotor and placed 120° apart can easily give this position information. This eliminates the need for the high-resolution encoder or position sensor required in PM synchronous machines, but the penalty paid for position sensor simplification is in performance. For EV/HEV applications, a high-resolution encoder/resolver may be necessary for phase advancing at high speeds. Vector control is not possible in PM brushless DC machines because of the trapezoidal shape of back-emfs.

The three-phase back-emf waveforms and the ideal phase currents of a PM brushless DC motor are shown in Figure 6.4. The back-emf waveforms are fixed with respect to rotor position. Square-wave phase currents are supplied such that they are synchronized with the back-emf peak of the respective phase. The controller achieves this objective using rotor position feedback information. The motor basically operates like a DC motor, with such a controller configuration, from a control point of view; hence, the motor is designated as a brushless DC motor.

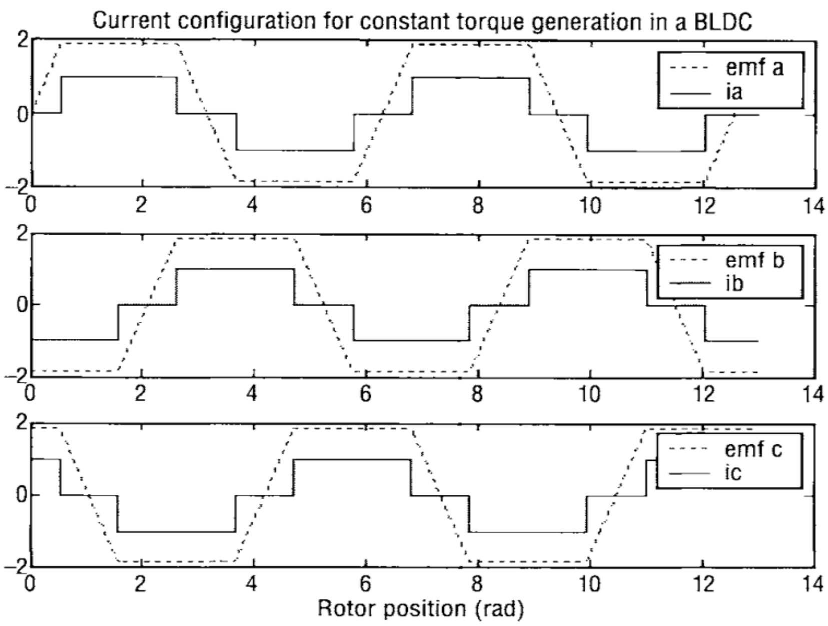


FIGURE 6.4 Back-emf and ideal phase currents in the three phases of a PM brushless DC motor.

Of the family of permanent magnetic motors, the brush-less DC (BLDC) motor drive is the most promising candidate for EV and HEV application. The major advantages of BLDC motor include:

The major advantages of BLDC motor include:

- High efficiency: BLDC motors are the most efficient of all electric motors. This is due to the use of permanent magnets for the excitation, which consume no power. The absence of a mechanical commutator and brushes means low mechanical friction losses and therefore higher efficiency.

- Compactness: The recent introduction of high-energy density magnets (rare-earth magnets) has allowed achieving very high flux densities in the BLDC motor. This makes it possible to achieve accordingly high torques, which in turns allows making the motor small and light.
- Ease of control: The BLDC motor can be controlled as easily as a DC motor because the control variables are easily accessible and constant throughout the operation of the motor.
- Ease of cooling: There is no current circulation in the rotor. Therefore, the rotor of a BLDC motor does not heat up. The only heat production is on the stator, which is easier to cool than the rotor because it is static and on the periphery of the motor.
- Low maintenance, great longevity, and reliability: The absence of brushes and mechanical commutators suppresses the need for associated regular maintenance and suppresses the risk of failure associated with these elements. The longevity is therefore only a function of the winding insulation, bearings, and magnet life-length.
- Low noise emissions: There is no noise associated with the commutation because it is electronic and not mechanical. The driving converter switching frequency is high enough so that the harmonics are not audible.

However, BLDC motor drives also suffer from some disadvantages such as:

- Cost: Rare-earth magnets are much more expensive than other magnets and result in an increased motor cost.
- Limited constant power range: A large constant power range is crucial to achieving high vehicle efficiencies. The permanent magnet BLDC motor is incapable of achieving a maximum speed greater than twice the base speed.
- Safety: Large rare-earth permanent magnets are dangerous during the construction of the motor because they may attract flying metallic objects toward them. In case of vehicle wreck, if the wheel is spinning freely, the motor is still excited by its magnets and high voltage is present at the motor terminals that can possibly endanger the passengers or rescuers.
- Magnet demagnetization: Magnets can be demagnetized by large opposing mmfs and high temperatures. The critical demagnetization force is different for each magnet material. Great care must be exercised when cooling the motor, especially if it is built compact.
- High-speed capability: The surface-mounted permanent magnet motors cannot reach high speeds because of the limited mechanical strength of the assembly between the rotor yoke and the permanent magnets.
- Inverter failures in BLDC motor drives: Because of the permanent magnets on the rotor, BLDC motors present major risks in case of

6.3.1 Basic Principles of BLDC Motor Drives

A BDLC motor drive consists mainly of the brush-less DC machine, a DSP-based controller, and a power electronics-based power converter, as shown in Figure 6.42. Position sensors *H*1, *H*2, and *H*3 sense the position of the machine rotor. The rotor position information is fed to the DSP-based controller, which, in turn, supplies gating signals to the power converter by turning on and turning off the proper stator pole windings of the machine. In this way, the torque and speed of the machines are controlled.

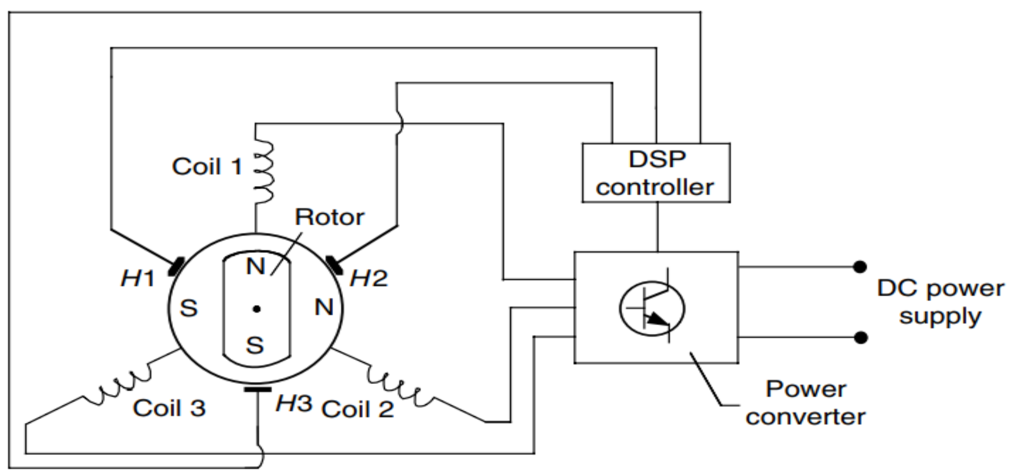


FIGURE 6.42
BLDC motor

Brushless DC Motor Modeling

The permanent magnet in the rotor can be regarded as a constant current source, giving rise to the back-emfs in the stator windings. The three stator windings for the three phases are assumed to be identical, with 120° (electrical) phase displacement among them. Therefore, the stator winding resistances and the self-inductance of each of the three phases can be assumed to be identical. Let R_s be the stator phase winding resistance, L_{aa}=L_{bb}=L_{cc}=L be the stator phase self-inductance, and L_{ab} =L_{ac}=L_{bc}=M stand for stator mutual inductance.

The voltage balance equation for the three phases are as follows:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R_s \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \cdot p \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{6.8}$$

where p is the operator d/dt, and e_a, e_b, and e_c are the back-emfs in the three phases. The back-emf is related to the phase flux-linkage as

$$e = \frac{d\lambda}{dt} = \frac{d\lambda}{d\theta_r} \cdot \frac{d\theta_r}{dt}$$

But, $d\theta_r/dt$=ω_r, which is the speed of the rotor. Then,

$$e = \omega_r \cdot \frac{d\lambda}{d\theta_r} \tag{6.9}$$

The back-emf will not have a trapezoidal shape during transient conditions. Similar to the back-emfs, the currents are also shifted by 120°, and they satisfy the condition $i_a+i_b+i_c=0$. Therefore, we have $M.i_b+M.i_c=-M\cdot i_a$. Similar expressions exist for the two other phases. Equation (6.8) can then be simplified to

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R_s \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \cdot p \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

The rate of change of currents for applied voltages can be expressed as

$$p \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{1}{L-M} \cdot \left[\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - R_s \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \right] \tag{6.10}$$

The electrical power transferred to the rotor is equal to the mechanical power $T_e\omega_r$ available at the shaft. Using this equality, the electromagnetic torque for the PM brushless DC motor is

$$T_e = \frac{e_a \cdot i_a + e_b \cdot i_b + e_c \cdot i_c}{\omega_r} \tag{6.11}$$

For the strategy described previously, where only two phase currents were active at one time, the torque expression for equal currents in two phases simplifies to

$$T_e = \frac{2 \cdot e_{\max} \cdot I}{\omega_r} \tag{6.12}$$

Because the currents are controlled to synchronize with the maximum back-emf only, e_{max} has been used in Equation 6.12 instead of e as a function of time or rotor position. Assuming magnetic linearity, Equation 6.9 can be written as

$$e = K \cdot \omega_r \cdot \frac{dL}{d\theta}$$

Hence, the maximum back-emf is

$$e_{\max} = K \cdot \left[\frac{dL}{d\theta}\right]_{\max} \cdot \omega_r$$

or

$$e_{\max} = K' \cdot \omega_r \tag{6.13}$$

Equations 6.12 and 6.13 are similar to the $E=K\cdot\Phi\cdot\omega$ and $T=K\cdot\Phi\cdot I$ equations associated with regular DC machines. Therefore, with the described control strategy, PM brushless DC motors can be considered as behaving like a DC machine.

6.3.4.2 Control of BLDC Motor Drives

In vehicle traction application, the torque produced is required to follow the torque desired by the driver and commanded through the accelerator and brake pedals. Thus, torque control is the basic requirement.

Figure 6.51 shows a block diagram of a torque control scheme for a BLDC motor drive. The desired current I^* is derived from the commanded torque T^* through a torque controller. The current controller and commutation sequencer receive the desired current I^* position information from the position sensors, and perhaps the current feedback through current transducers, and then produces gating signals. These gating signals are sent to the three-phase inverter (power converter) to produce the phase current desired by the BLDC machine.

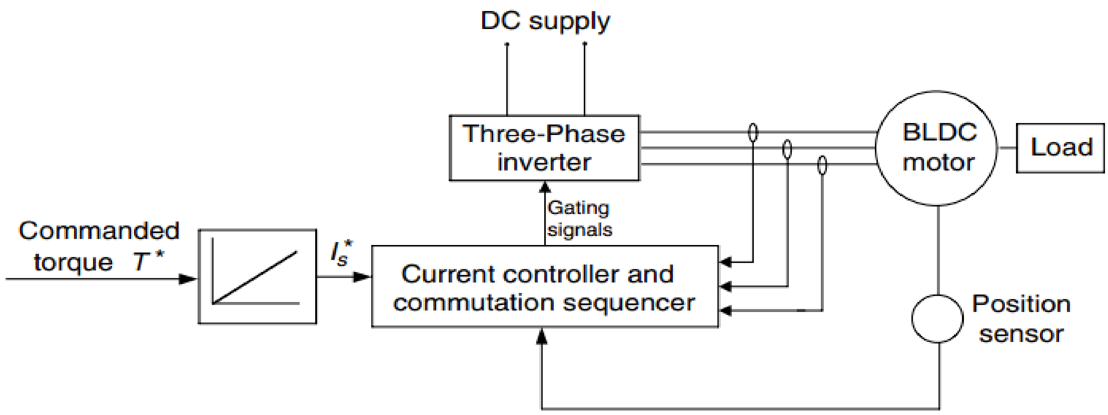


FIGURE 6.51
Block diagram of the torque control of the BLDC motor

In traction application, speed control may be required, cruising control operation, for example (see Figure 6.52). Many high-performance applications include current feedback for torque control. At the minimum, a DC bus current feedback is required to protect the drive and machine from overcurrents. The controller blocks, "speed controller" may be any type of classical controller such as a PI controller, or a more advanced controller such as an artificial intelligence control. The "current controller and commutation sequencer" provides the properly sequenced gating signals to the "three-phase inverter" while comparing sensed currents to a reference to maintain a constant peak current control by hysteresis (current chopping) or with a voltage source (PWM)-type current control. Using position information, the commutation sequencer causes the inverter to "electronically commutate," acting as the mechanical commutator of a conventional DC machine. The commutation angle associated with a brush-less motor is normally set so that the motor will commutate around the peak of the torque angle curve. Considering a three-phase motor, connected in delta or wye, commutation occurs at electrical angles, which are ±30° (electrical) from the peaks of the torque–angle curves. When the motor position moves beyond the peaks by an amount equal to 30° (electrical), then the commutation sensors cause the stator phase excitation to switch to move the motor suddenly to −30° relative to the peak of the next torque–angle curve.[77]

6.3.5 Extension of Speed Technology

As discussed above, PM BLDC machines inherently have a short constant power range due to their rather limited field weakening capability. This is a result of the presence of the PM field, which can only be weakened through the production of a stator field component that opposes the rotor magnetic field. The speed ratio, x, is usually less than 2.[8]

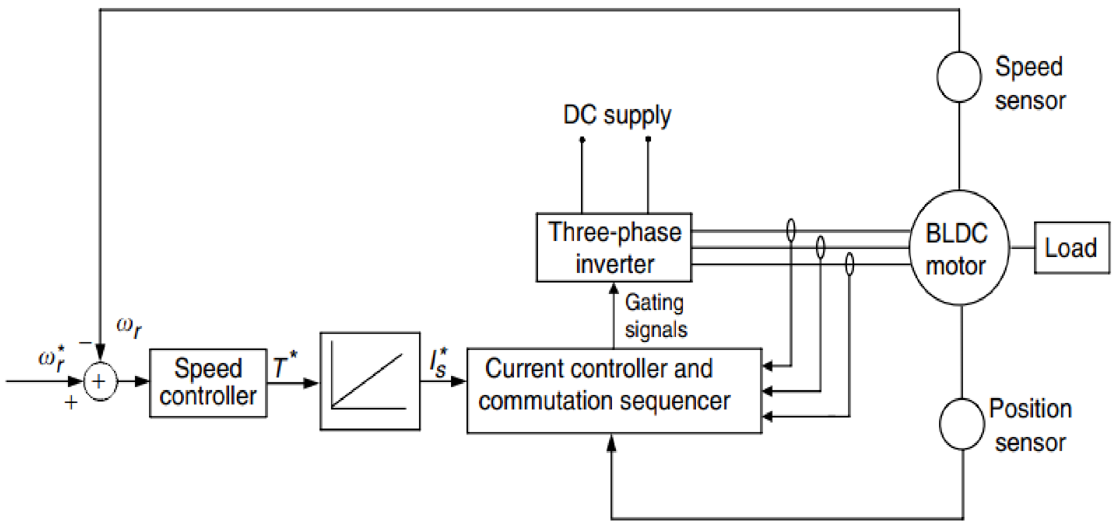


FIGURE 6.52
Block diagram of the speed control of the BLDC motor

Recently, the use of additional field windings to extend the speed range of PM BLDC motors has been developed.[1] The key is to control the field current in such a way that the air gap field provided by PMs can be weakened during high-speed constant-power operation. Due to the presence of both PMs and the field windings, these motors are called PM hybrid motors. The PM hybrid motor can achieve a speed ratio of around 4. The optimal efficiency profiles of a PM hybrid motor drive are shown in Figure 6.53.[1] However, the PM hybrid motors have the drawback of a relatively complex structure. The speed ratio is still not enough to meet the vehicle performance requirement, especially in an off-road vehicle. Thus, a multigear transmission is required.

5.Switch reluctance motors: Merits limitations - converter configuration - control of SRM for EV/HEV's

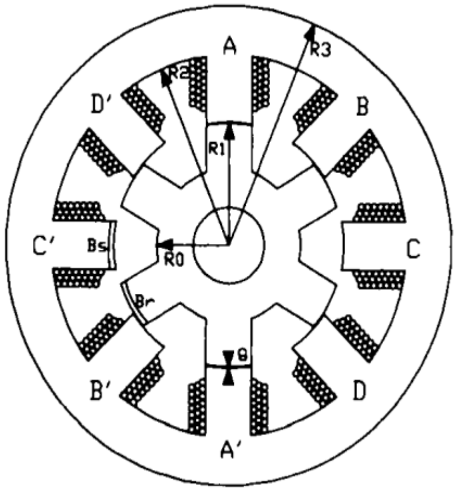
SWITCHED RELUCTANCE MACHINES

6.2.1
SRM CONFIGURATION

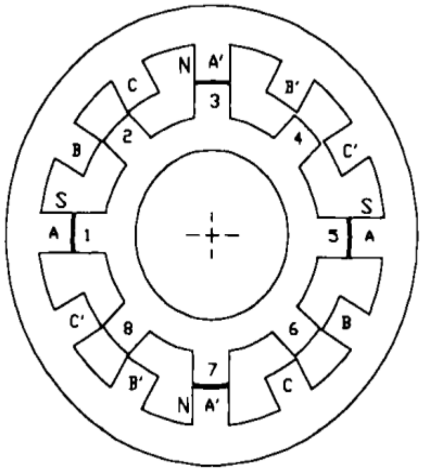
The switched reluctance motor (SRM) is a doubly salient, singly excited reluctance machine with independent phase windings on the stator. The stator and the rotor are made of magnetic steel laminations, with the latter having no windings or magnets. Cross-sectional diagrams of a four-phase, 8/6 SRM and a three-phase, 12/8 SRM are shown in Figure 6.5. The three-phase, 12/8 machine is a two-repetition version of the basic 6/4 structure within the single stator geometry. The two-repetition machine can alternately be labeled as a four-poles/phase machine, compared to the 6/4 structure with two poles/phase. The stator windings on diametrically opposite poles are connected in series or in parallel to form one phase of the motor. When a stator phase is energized, the most adjacent rotor pole-pair is attracted toward the energized stator in order to minimize the reluctance of the magnetic path. Therefore, it is possible to develop constant torque in either direction of rotation by energizing consecutive phases in succession.

The aligned position of a phase is defined to be the orientation when the stator and rotor poles of the phase are perfectly aligned, attaining the minimum reluctance position. The unsaturated phase inductance is maximum (L_a) in this position. Phase inductance decreases gradually as the rotor poles move away from the aligned position in either direction. When the rotor poles are symmetrically misaligned with the stator poles of a phase, the position is said to be the unaligned position. The phase has the minimum inductance (L_u) in this position. Although the concept of inductance is not valid for a highly saturating machine like SRM, the unsaturated aligned and unaligned inductances are two key reference positions for the controller.

Several other combinations of the number of stator and rotor poles exist, such as 10/4, 12/8, etc. A 4/2 or a 2/2 configuration is also possible, but if the stator and rotor poles are aligned exactly, then it would be impossible to develop a starting torque. Configurations with a higher number of stator/rotor pole combinations have less torque ripple and do not have the problem of starting torque.



(a)



(b)

FIGURE 6.5 Cross-sections of three-phase SR machines: (a) four-phase 8/6 structure; (b) 12/8, two-repetition (two-channel) structure. (From Husain, I., Switched reluctance machines, in *The Power Electronics Handbook,* Skvarenina, T.L., Ed., CRC Press, Boca Raton, FL, 2002.)

Advantages and Drawbacks

Switched reluctance machines or motors (SRM) possess unique features that make them strong competitors to existing AC and DC motors in various adjustable speed drives and servo applications. The advantages of an SRM can be summarized as follows:

- Simple and low-cost machine construction due to the absence of rotor winding and permanent magnets.
- No shoot-through faults between the DC buses in the SRM drive converter, because each phase winding is connected in series with converter switching elements.
- Bidirectional currents are not necessary, which facilitates the reduction of the number of power switches in certain applications.
- The bulk of the losses appears in the stator, which is relatively easier to cool.
- The torque-speed characteristics of the motor can be tailored to the application requirement more easily during the design stage than in the case of induction and PM machines.
- The starting torque can be very high without the problem of excessive inrush current due to its higher self-inductance.
- The maximum permissible rotor temperature is higher, because there is no permanent magnet.

- They have low rotor inertia and high torque/inertia ratio.
- They make extremely high speeds with a wide constant power region possible.
- Independent stator phases enable drive operation in spite of the loss of one or more phases.

The SRM also comes with a few disadvantages, among which torque ripple and acoustic noise are the most critical. The double saliency construction and the discrete nature of torque production by the independent phases lead to higher torque ripple compared to other machines. The higher torque ripple also causes the ripple current in the DC supply to be quite large, necessitating a large filter capacitor. The doubly salient structure of the SRM also causes higher acoustic noise compared to other machines. The main source of acoustic noise is the radial magnetic force-induced resonance with the circumferential mode shapes of the stator. Among other disadvantages of SR motors are special converter and higher terminal connection requirements that add cost to the system.

The absence of permanent magnets imposes the burden of excitation on the stator windings and converter, which increases the converter kVA requirement. Compared to PM brushless machines, the per-unit stator copper losses will be higher, reducing the efficiency and torque per ampere. However, maximum speed at constant power is not limited by the fixed magnet flux as in the PM machine, and hence, an extended constant power region of operation is possible in SRMs. The control can be simpler than the field-oriented control of induction machines, although for torque ripple minimization, significant computations may be required for an SRM drive.

Torque Production

Torque is produced in the SRM by the tendency of the rotor to attain the minimum reluctance position when a stator phase is excited. The general expression for instantaneous torque for such a device that operates under the reluctance principle is as follows:

$$T_{ph}\left(\theta, i_{ph}\right) = \left.\frac{\partial W'\left(\theta, i_{ph}\right)}{\partial \theta}\right|_{i=\text{constant}} \tag{6.19}$$

where W′ is the co-energy defined as

$$W' = \int_0^i \lambda_{ph}\left(\theta, i_{ph}\right) di$$

Obviously, instantaneous torque is not constant. Total instantaneous torque of the machine is given by the sum of the individual phase torques:

$$T_{inst}(\theta, i) = \sum_{phases} T_{ph}\left(\theta, i_{ph}\right) \tag{6.20}$$

SRM electromechanical properties are defined by the static T—i—θ characteristics of a phase, an example of which is shown in Figure 6.8. Average torque is a more important parameter from the user's perspective and can be derived mathematically by integrating Equation 6.20:

$$T_{avg} = \frac{1}{T}\int_0^T T_{inst}\, dt \tag{6.21}$$

Average torque is also an important parameter during the design process.

When magnetic saturation can be neglected, instantaneous torque expression becomes:

$$T_{ph}(\theta, i) = \frac{1}{2} i_{ph}^2 \frac{dL_{ph}(\theta)}{d\theta} \tag{6.22}$$

The linear torque expression also follows from the energy conversion term (last term) in Equation 6.17. The phase current needs to be synchronized with the rotor position for effective torque production. For positive or motoring torque, the phase current is switched so that the rotor is moving from the unaligned position toward the aligned position. The linear SRM model is insightful in understanding these situations. Equation 6.22 clearly shows that for motoring torque, the phase current must coincide with the rising inductance region. On the other hand, the phase current must coincide with the decreasing inductance

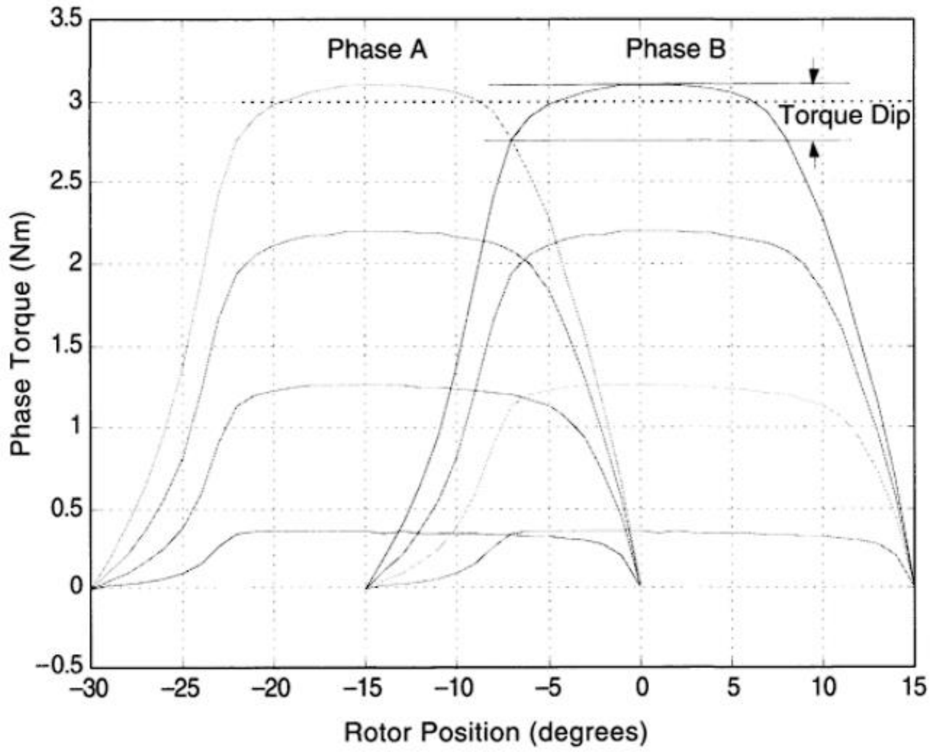


FIGURE 6.8 Torque-angle-current characteristics of a four-phase SRM for four constant current levels. (From Husain, I., Switched reluctance machines, in *The Power Electronics Handbook,* Skvarenina, T.L., Ed., CRC Press, Boca Raton, FL, 2002.)

region for braking or generating torque. The phase currents for motoring and generating modes of operation are shown in Figure 6.9, with respect to the phase inductance profiles. Torque expression also shows that the direction of current is immaterial in torque production. The optimum performance of the drive system depends on the appropriate positioning of phase currents relative to the rotor angular position. Therefore, a rotor position transducer is essential to provide the position feedback signal to the controller.

6.2.2.4 Torque-Speed Characteristics

The torque-speed plane of an SRM drive can be divided into three regions, as shown in Figure 6.10. The constant torque region is the region below the base speed ω_b, which is defined as the highest speed when maximum rated current can be applied to the motor at rated voltage with fixed firing angles. In other words, ω_b is the lowest possible speed for the motor to operate at its rated power.

Region 1: In the low speed region of operation, the current rises almost instantaneously after turn on, because the back-emf is small. The current can be set at any desired level by means of regulators, such as hysteresis controller or voltage pulse width modulation (PWM) controller.

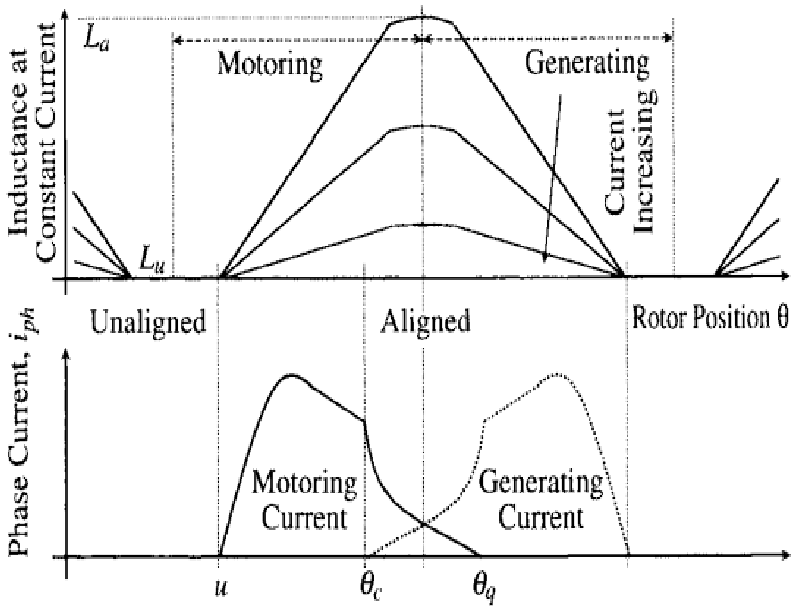


FIGURE 6.9 Phase currents for motoring and generating modes with respect to rotor position and idealized inductance profiles. (From Husain, I., Switched reluctance machines, in *The Power Electronics Handbook,* Skvarenina, T.L., Ed., CRC Press, Boca Raton, FL, 2002.)

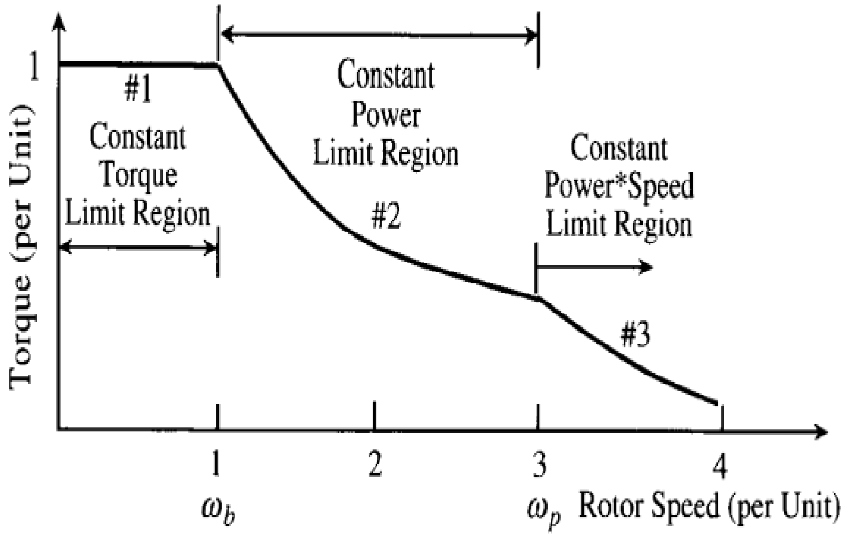


FIGURE 6.10 Torque-speed characteristics of an SRM drive. (From Husain, I., Switched reluctance machines, in *The Power Electronics Handbook,* Skvarenina, T.L., Ed., CRC Press, Boca Raton, FL, 2002.)

As the motor speed increases, the back-EMF soon becomes comparable to the DC bus voltage, and it is necessary to phase advance the turn-on angle so that the current can rise to the desired level against a lower back-EMF. Maximum current can still be forced into the motor by PWM or chopping control to maintain the maximum torque production. The phase excitation pulses also need to be turned off a certain time before the rotor passes alignment to allow the freewheeling current to decay so that no braking torque is produced.

Region 2: When the back-EMF exceeds the DC bus voltage in high-speed operation, the current starts to decrease once pole overlap begins and PWM or chopping control is no longer possible. The natural characteristic of the SRM, when operated with fixed supply voltage and fixed conduction angle θ_{dwell} (also known as the dwell angle), begins when the phase excitation time falls off inversely with speed and so does the current. Because torque is roughly proportional to the square of the current, the rapid fall in torque with speed is countered by adjusting the conduction angle. Increasing the conduction angle increases the effective amps delivered to the phase. Torque production is maintained at a level high enough in this region by adjusting the conduction angle $\theta dwell$ with the single-pulse mode of operation. The controller maintains the torque inversely proportional to the speed; hence, this region is called the constant power region. The conduction angle is also increased by advancing the turn-on angle until the θ_{dwell} reaches its upper limit at speed ω_p.

The medium speed range through which constant power operation can be maintained is quite wide, and high maximum speeds can be achieved.

Region 3: The θ_{dwell} upper limit is reached when it occupies half the rotor pole-pitch, i.e., half the electrical cycle. θ_{dwell} cannot be increased further, because the flux would not return to zero, and the current conduction would become continuous. The torque in this region is governed by natural characteristics, falling off as $1/\omega^2$.

The torque-speed characteristics of the SRM are similar to a DC series motor, which is not surprising, considering that the back-emf is proportional to current, while the torque is proportional to the square of the current.

SR MOTOR DRIVES

The power electronic drive circuits for SR motor drives are different from those of AC motor drives. The torque developed in an SR motor is independent of the direction of current flow. Therefore, unipolar converters are sufficient to serve as the power converter circuit for the SR motor, unlike induction motors or synchronous motors, which require bidirectional currents. This unique feature of the SR motor, together with the fact that the stator phases are electrically isolated from one another, generated a wide variety of power circuit configurations. The type of converter required for a particular SR motor drive is intimately related to motor construction and the number of phases. The choice also depends on the specific application.

SRM CONVERTERS

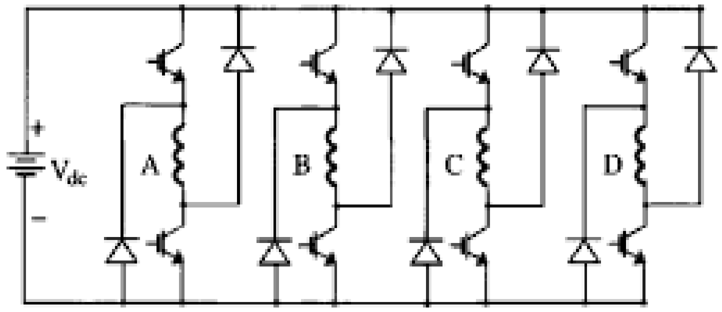
The most flexible and the most versatile four-quadrant SRM converter is the bridge converter, shown in Figure 8.23a, which requires two switches and two diodes per phase.[7,8] The switches and the diodes must be rated to withstand the supply voltage plus any transient overload. During the magnetization period, both switches are turned on, and the energy is transferred from the source to the motor. Chopping or PWM, if necessary, can be accomplished by switching either or both of the switches during the conduction period, according to the control strategy. At commutation, both switches are turned off, and the motor phase is quickly defluxed through the freewheeling diodes. The main advantage of this converter is the independent control of each phase, which is particularly important when phase overlap is desired. The only disadvantage is the requirement of two switches and two diodes per phase. This converter is especially suitable for high-voltage, high-power drives.

The split-capacitor converter shown in Figure 8.23b has only one switch per phase but requires a split DC supply.[7] The phases are energized through the upper or the lower DC bus rail and the midpoint of the two capacitors. Therefore, only one-half the DC bus voltage can be applied for torque production. In order to maintain power flow balance between the two supply capacitors, the switching device and the freewheeling diode are transposed for each phase winding, which means that the motor must have an even number of phases. Also, the power devices must be rated to withstand the full DC supply voltage.

In low-speed applications, where PWM current control is desirable over the entire range of operation, the bridge converter can be reduced to the circuit shown in Figure 8.23c, developed by Miller.[8] In this converter, chopping is performed by one switch common to all phases. The circuit requires (n+1) switches for an n-phase motor. The main limitation of this circuit is that at higher speeds, the off-going phase cannot be de-energized fast enough, because the control switch Q1 keeps turning on intermittently, disabling forced demagnetization. A class of power converter circuits with less than two switches per phase for SR motors having four or more phases has been developed by Pollock and Williams.[9]

The energy-efficient C-dump converter shown in Figure 8.23d is a regenerative converter topology with a reduced number of switches.[10] The topologies were derived from the C-dump converter proposed earlier by Miller.[8] The energy-efficient converter topologies eliminate all the disadvantages of the C-dump converter without sacrificing its attractive features, and they also provide additional advantages. The attractive features of the converters include a lower number of power devices, full regenerative capability, freewheeling in chopping or PWM mode, simple control strategy, and faster demagnetization during commutation. The energy-efficient C-dump converter has one switch plus one diode forward voltage drop in the phase magnetization paths.

Converters with a reduced number of switches are typically less fault-tolerant compared to the bridge converter. The ability to survive component or motor phase failure should be a prime consideration for high-reliability applications. On the other hand, in low-voltage applications, the voltage drop in two switches can be a significant percentage of the total bus voltage, which may not be affordable. Among other factors to be considered in selecting a drive circuit are cost, complexity in control, number of passive components, number of floating drivers required, etc. The drive converter must be chosen to serve the particular needs of an application.



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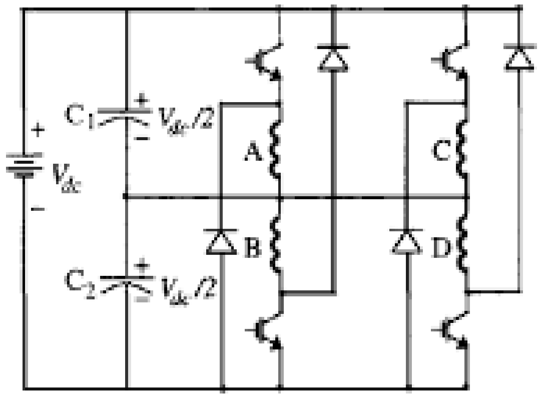

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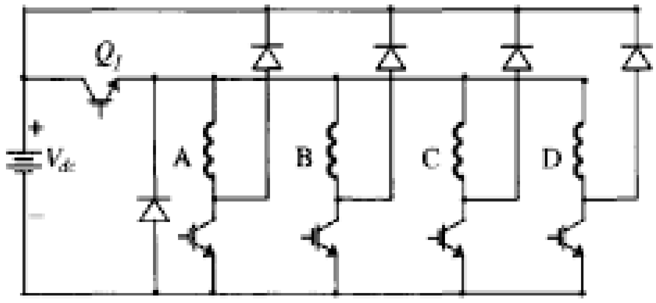

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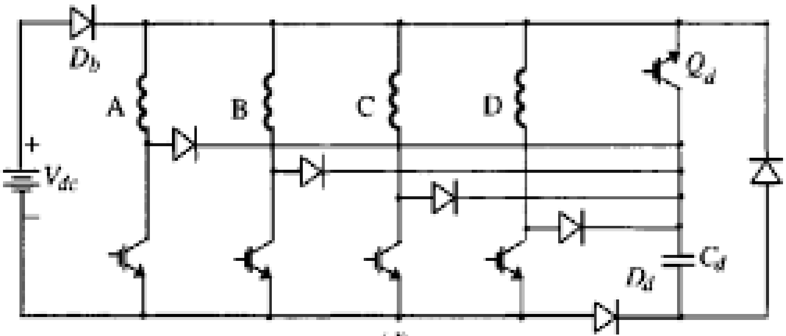

(d)

FIGURE 8.23 Converter topologies for SRM: (a) classic bridge power converter; (b) split-capacitor converter; (c) Miller converter; and (d) energy-efficient converter.

SRM CONTROLS

Appropriate positioning of the phase excitation pulses relative to the rotor position is the key in obtaining effective performance out of an SR motor drive system. The turn-on time, the total conduction period, and the magnitude of the phase current determine torque, efficiency, and other performance parameters. The type of control to be employed depends on the operating speed of the SRM.

8.4.2.1
Control Parameters

The control parameters for an SR motor drive are the turn-on angle (θ_{on}), turn-off angle (θ_{off}), and the phase current. The conduction angle is defined as $\theta_{dwell}=\theta_{off}-\theta_{on}$. The complexity of determination of the control parameters depends on the chosen control method for a particular application. The current command can be generated for one or more phases depending on the controller. In voltage-controlled drives, the current is indirectly regulated by controlling the phase voltage.

At low speeds, the current rises almost instantaneously after turn-on due to the negligible back-emf, and the current must be limited by controlling the average voltage or regulating the current level. The type of control used has a marked effect on the performance of the drive. As the speed increases, the back-emf increases, as explained before, and opposes the applied bus voltage. Phase advancing is necessary to establish the phase current at the onset of the rotor and stator pole overlap region. Voltage PWM or chopping control is used to force maximum current into the motor in order to maintain the desired torque level. Also, phase excitation is turned off early enough so that phase current decays completely to zero before the negative torque-producing region is reached.

At higher speeds, the SRM enters the single-pulse mode of operation, where the motor is controlled by advancing the turn-on angle and adjusting the conduction angle. At very high speeds, the back-emf will exceed the applied bus voltage once the current magnitude is high and the rotor position is appropriate, which causes the current to decrease after reaching a peak, even though a positive bus voltage is applied during the positive $dL/d\theta$. The control algorithm outputs θ_{dwell} and θ_{on} according to speed. At the end of θ_{dwell}, the phase switches are turned off so that negative voltage is applied across the phase to commutate the phase as quickly as possible. The back-emf reverses polarity beyond the aligned position and may cause the current to increase in this region, if the current does not decay to insignificant levels. Therefore, the phase commutation must precede the aligned position by several degrees so that the current decays before the negative $dL/d\theta$ region is reached.

In the high-speed range of operation, when the back-emf exceeds the DC bus voltage, the conduction window becomes too limited for current or voltage

control, and all the chopping or PWM has to be disabled. In this range, θ_{dwell} and θ_{adv} are the only control parameters, and control is accomplished based on the assumption that approximately θ_{dwell} regulates torque and θ_{adv} determines efficiency.

8.4.2.2
Advance Angle Calculation

Ideally, the turn-on angle is advanced such that the reference current level i* is reached just at the onset of pole overlap. In the unaligned position, phase inductance is almost constant, and hence, during turn-on, back-emf can be neglected. Also, assuming that the resistive drop is small, Equation 6.6 can be written as

$$V_{ph} = L(\theta)\frac{\Delta i}{\Delta\theta}\omega \tag{8.29}$$

Now, $\Delta i = i^*$ and $\Delta\theta = \theta_{overlap} - \theta_{on} = \theta_{\mathrm{adv}}$, where $\theta_{overlap}$ is the position where pole overlap begins, θ_{on} is the turn-on angle, and θ_{adv} is the required phase turn-on advance angle. Therefore, we have

$$\theta_{adv} = L_u\omega\frac{i^*}{V_{dc}} \tag{8.30}$$

The above simple advance angle θ_{adv} calculation approach is sufficient for most applications, although it does not account for the errors due to neglecting the back-emf and the resistive drop in the calculation.

8.4.2.3
Voltage-Controlled Drive

In low-performance drives, where precise torque control is not a critical issue, fixed-frequency PWM voltage control with variable duty cycle provides the simplest means of control of the SRM drive. A highly efficient variable speed drive having a wide speed range can be achieved with this motor by optimum use of the simple voltage feeding mode with closed-loop position control only. The block diagram of the voltage-controlled drive is shown in Figure 8.24. The angle controller generates the turn-on and turn-off angles for a phase, depending on the rotor speed, which simultaneously determines the conduction period, θ_{dwell}. The duty cycle is adjusted according to the voltage command signal. The electronic commutator generates the gating signals based on the control inputs and the instantaneous rotor position. A speed feedback loop can be added on the outside, as shown when precision speed control is desired. The drive usually incorporates a current sensor typically placed on the lower leg of the DC link for overcurrent protection. A current feedback loop can also be added that will further modulate the duty cycle and compound the torque-speed characteristics, just like the armature voltage control of a DC motor.

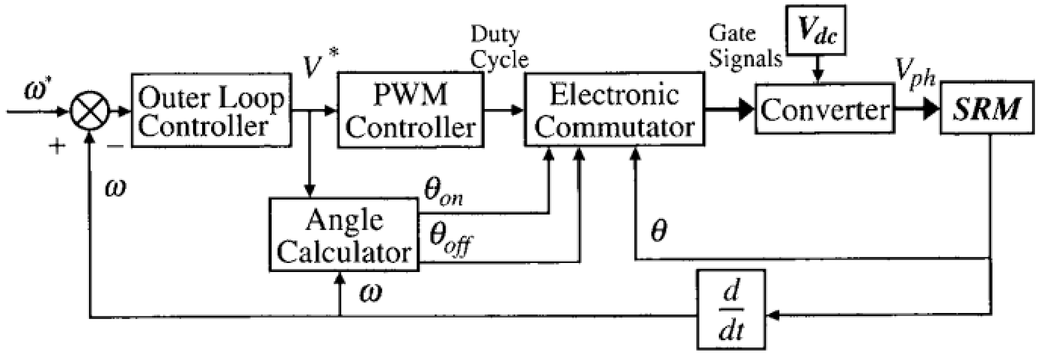

FIGURE 8.24 Voltage-controlled drive.

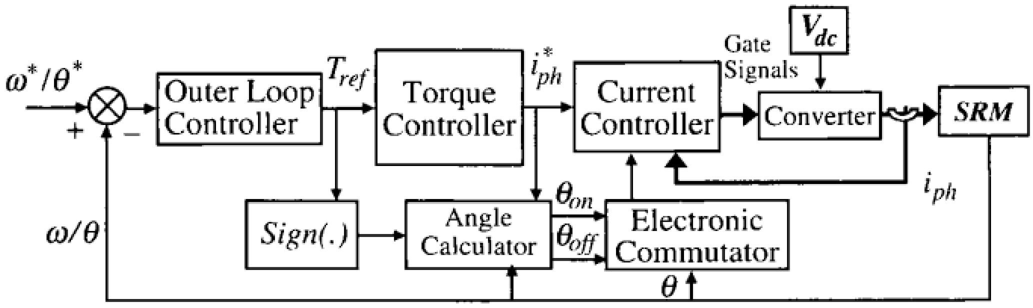

FIGURE 8.25 Current-controlled drive.

Current-Controlled Drive

In torque-controlled drives, such as in high-performance servo applications, the torque command is executed by regulating the current in the inner loop, as shown in Figure 8.25. The reference current i^* for a given operating point is determined from the load characteristics, the speed, and the control strategy. A wide-bandwidth current transducer provides the current feedback information to the controller from each of the motor phases. This mode of control allows rapid resetting of the current level and is used where fast motor response is desired. For loads with torque that increases monotonically with speed, such as in fans or blowers, speed feedback can be introduced in the outer loop for accurate speed control.

The simpler control strategy is to generate one current command to be used by all the phases in succession. The electronic commutator (see Figure 8.25) selects the appropriate phase for current regulation based on θ_{on}, θ_{off}, and the instantaneous rotor position. The current controller generates the gating signal for the phases based on the information coming from the electronic commutator. The current in the commuated phase is quickly brought down to zero, applying negative V_{dc}, while the incoming phase assumes the responsibility of torque production based on the commanded current. The phase transition in these drives is not smooth, which tends to increase the torque ripple of the drive.

Advanced Control Strategies

A higher performance index, such as torque/ampere maximization, efficiency maximization, or torque ripple minimization can be required in certain applications. For example, in direct drive or traction applications, the efficiency over a wide speed range is critical. For applications, such as electric power steering in automobiles, the torque ripple is a critical issue. Typically, the torque/ampere maximization will go hand in hand with efficiency maximization, while torque ripple minimization will require the sacrifice of efficiency to a certain extent.

The high-performance drives will typically be current-controlled drives with sophistication added to the controller discussed earlier. For efficiency maximization, the key issue is the accurate determination of θ_{on} and θ_{off}, which may require modeling of the SRM and online parameter identification.[11] The modeling issue is equally important for torque ripple minimization, where the overlapping phase currents are carefully controlled during commutation.[12] In these sophisticated drives, the electronic commutator works in conjunction with the torque controller to generate the gating signals. The torque controller will include a model or tables describing the characteristics of the SRM.

The use of an indirect position sensing or sensorless method to eliminate the discrete position sensors is highly desirable for cost reduction and reliability enhancement purposes. All of the indirect position sensing methods developed for SR motors utilize the reluctance variation information along the air gap in one way or another. The position estimation is easily possible in SR motors, even at zero speed, because its inductance/flux varies in accordance with the rotor position. Some of the methods apply a diagnostic pulse in an unenergized phase to extract the rotor position information. A motor can be a good sensor of the motion, when its voltages and currents possess sufficient information to determine its position and velocity. Some of the observer-based methods depend on terminal measurements of voltages and currents.